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Complex terrain: from spectra and form drag to effective roughness and flow simulation

Mark Kelly, Dalibor Cavar, and Andrey Sogachev

Danish Technical University, Risø Lab/Campus, DTU Wind Energy, RAM (Resource Assessment, meteorological Modeling), Roskilde, Denmark (mkel@dtu.dk)

The aggregate effect of drag caused by complex terrain has consequences on atmospheric flow modelling across a broad range of spatial scales. This includes large-scale simulations such as climate models (with resolutions of tens of km or larger) and mesoscale simulations, as well as finer flow models such as RANS (Reynolds-Averaged Navier-Stokes) solvers and LES (Large-Eddy Simulation), where the latter calculate solutions at resolutions corresponding to turbulent motions. Computational flow models at coarser resolutions capture less terrain drag, which includes pressure-induced 'form' drag as well as air-surface momentum exchange due to terrain-enhanced turbulence. Models resolving a smaller proportion of terrain slopes must rely more on parameterizing unresolved stresses and pressure-strain effects, or employ a bulk correction such as using larger effective surface roughness lengths (z_0). The latter is more applicable above some height, averaged over horizontal scales much larger than the variations of terrain elevation.

Previous works have included development of simple (height-dependent) stress prescriptions based on assumed forms of terrain spectra, as well as more recent forms for effective roughness based on the variance of terrain elevation and/or spectral exponent of terrain spectra. Here we investigate effective z_0 from terrain spectra and associated statistics; this includes development of a general form linking the 'outer turbulence length scale' from spectral/analytical flow modeling, with the variance of terrain elevation changes and the spectral exponent (alternately fractal dimension)—within the range of scales relevant for a given atmospheric flow model resolution and domain size. We evaluate our general form within the context of more specific forms such as those treating viscous-scale roughness and surface-elevation spectral exponent, also considering extension of the specific form for broader atmospheric use. We further examine relation between the variance in our general form and other terrain metrics, for practical use.

To empirically tune our z_0 prescriptions for practical use, we focus on their application via fine-resolution (10–20m) RANS modelling. We examine the height-dependent spatially integrated effect of turbulent drag both in terms of stress and in comparison with our effective z_0 prescription, also finding a potential new metric for effective blending height (with regard to RANS simulations having 2-equation turbulence models, but extensible to others). The effective roughness results and parameterization are not just amenable to correcting or driving atmospheric RANS simulations, but also to treating terrain drag at scales on the order of our various computational domains (e.g. not resolved by mesoscale or climate models).